IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re Application of

Newns, et al. **Patent No.:** 6,984,846 B2

Serial No.: 10/648,346 **Group Art Unit:** 2811

Filed: August 27, 2003 **Examiner:** Crane, S.

For: A GRADIOMETER-BASED FLUX QUBIT FOR QUANTUM COMPUTING AND METHOD THEREFOR

Honorable Commissioner for Patents
P.O. Box 1450
Alexandria, VA 22313-1450

Attn: Certificate of Correction Branch

REQUEST FOR CERTIFICATE OF CORRECTION

Sir:

The undersigned respectfully requests a Certificate of Correction for the above identified patent. In particular:

In column 1, lines 8-9, delete:

"The subject matter of the present Application was at least partially funded under the"... and insert:

"This invention was made with Government support under"...; and

In column 1, line 11, after "(DARPA).", insert:

"The Government has certain rights to this invention".

Please forward a Certificate of correction, showing these corrections to the address shown below. If there are any questions on this matter, please direct all telephone calls to the number shown below.

Serial No.: 10//648,846 B2
Patent No.: 6,984,846 B2

The Commissioner is hereby authorized to charge a fee of $100.00 and charge any deficiency in fees or to credit any overpayment in fees to Attorney's Deposit Account No. 50-0481.

Respectfully Submitted,

Date: 2/2/07

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(Also Form PTO-1050)

UNITED STATES PATENT AND TRADEMARK OFFICE
CERTIFICATE OF CORRECTION

PATENT NO. : **US 6,984,846 B2**

DATED : **January 10, 2006**

INVENTOR(S) : **Dennis M. Newns, et al.**

It is certified that an error appears or errors appear in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Column 1, lines 8-9, delete:

"The subject matter of the present Application was at least partially funded under the" and

insert:

"This invention was made with Government support under"...;

Column 1, line 11, after "(DARPA)." , insert

"The Government has certain rights to this invention."

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PATENT NO. US 6,984,846

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P15/REV03

This invention was made with Government support under

GRADIOMETER-BASED FLUX QUBIT FOR QUANTUM COMPUTING AND METHOD THEREFOR

U.S. GOVERNMENT RIGHTS IN THE INVENTION

~~The subject matter of the present Application was at least partially funded under the~~ Grant No. MDA972-01-C-0052 from the U.S. Defense Advanced Research Projects Agency (DARPA). The Government has certain rights to this invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to a quantum computer. Specifically, a quantum bit (qubit) based on a gradiometer superconducting flux qubit design provides significant noise immunity and two independent input controls, one each for S_x and S_z fields.

2. Description of the Related Art

Relative to classical computers, a quantum computer potentially offers an enormous gain in the use of computational resources, including time and memory. Classical computers need exponentially more time or memory to match the computational power of a quantum computer when appropriate problems are addressed.

Experimental and theoretical research in quantum computation is accelerating world-wide. New technologies for realizing quantum computers have been proposed and continue to be further analyzed and improved.

The basic unit of quantum information in a quantum computer is a quantum two-state system, called a "quantum bit" ("qubit"). A qubit is a superposition of its two logical states 0 and 1. Thus, a qubit can encode, at a given moment of time, both 0 and 1.

An ideal hardware implementation of the qubit should be: 1) a controllable high-coherence (e.g., Q-factor, the time for which the wavefunction remains quantum-coherent, per unit time required to implement a qubit operation—of at least 10^5) quantum 2-level system, and 2) scalable (i.e., many qubits, for example, 10^4, can be manufactured and operated cheaply).

A key element in the search for practical quantum computer designs is finding an improved hardware implementation of the qubit. After successes with few-qubit systems, including demonstration of the Schor factorization algorithm with NMR (Nuclear Magnetic Resonance)-based techniques, further progress awaits development of scalable qubits. For example, existing qubit implementations (such as by NMR) have achieved limited success (such as demonstrating factorization of 15), but have run into limitations of non-scalability.

Using lithography, for example, manufacture of the thousands of similar qubits required in a practical quantum computer becomes feasible. One scalable approach being explored implements the qubit as a micron-scale superconducting circuit. Recently, superconducting implementations with a long coherence lifetime, approaching that required for realistic quantum computation, have been demonstrated.

For example, a type of superconducting Josephson-junction qubit has recently been shown to have a Q-factor of order 10^4, which approaches that required in a quantum computer. Such qubits can be cheaply made in multiple copies on a chip by lithography, and are, therefore, scalable. However, the approach described is a charge qubit, whose states are defined in terms of the presence or absence of a single electron-pair, and, therefore, is likely to lack robustness for a commercial environment.

Thus, the conventional superconducting qubits have either involved a nanoscopic quantum dot, whose bistable state is defined by the presence/absence of a single electron pair, or operate in an intermediate regime where the defined state is a hybrid of charge and flux (sometimes termed a 'phase' qubit).

SUMMARY OF THE INVENTION

Given the potential delicacy of single electron pair-based devices in an engineering context, it is important at this initial stage of qubit development to explore potentially more robust designs. More specifically, in the flux qubit design, the approach taken in the present invention, the bistable state is defined by clockwise/anticlockwise circulation of currents in a superconducting ring (or, equivalently, the associated ↑- and ↓-polarity magnetic fluxes).

Such a qubit would have intrinsic robustness, as well as scalability and a high Q-factor.

So far, there has been no successful demonstration of a flux qubit. In addition to scalability, such devices would require very careful engineering design in order to satisfy the following criteria:

a) significant inter-state tunneling, which only occurs in a narrow parameter range;

b) high Q-factor (i.e., noise immunity);

c) controllability (i.e., two, preferably independent, input circuits);

d) readout capability; and

e) analyzability.

Therefore, in view of the foregoing problems, drawbacks, and disadvantages of the conventional systems, it is an exemplary feature of the present invention to provide a structure for a qubit that is robust, scalable, and has a high Q-factor.

It is another exemplary feature of the present invention to provide a flux qubit structure in which a gradiometer design provides independent control of the S_x and S_z fields and possesses a degree of immunity to flux noise in both these fields.

To achieve the above and other exemplary features and advantages, in a first exemplary aspect of the present invention, described herein is a qubit (quantum bit) circuit including a superconducting main loop that is electrically-completed by a serially-interconnected superconducting subloop. The subloop preferably contains two Josephson junctions. A first coil provides a first flux that couples with the main loop, but not necessarily with the subloop. A second coil provides a second flux that couples with the subloop but not necessarily with the main loop.

In a second exemplary aspect of the present invention, described herein is a qubit (quantum bit) circuit including a superconducting main loop that is electrically-completed by a serially-interconnected superconducting subloop. The subloop contains two Josephson junctions. A noise immunity characteristic of the main loop is enhanced by selection of an operating point such that fluctations in flux affect an eigenvalue of a potential energy function of the main loop only to a second order. The noise immunity characteristic of the subloop is enhanced by forming the subloop in a shape such that a uniform field representing a noise is canceled out in the subloop.

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(12) United States Patent
Newns et al.

(10) Patent No.: US 6,984,846 B2
(45) Date of Patent: Jan. 10, 2006

(54) **GRADIOMETER-BASED FLUX QUBIT FOR QUANTUM COMPUTING AND METHOD THEREFOR**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 45 days.

(21) Appl. No.: **10/648,346**

(22) Filed: **Aug. 27, 2003**

(65) **Prior Publication Data**

US 2005/0045872 A1 Mar. 3, 2005

(51) **Int. Cl.**
H01L 29/06 (2006.01)

(52) **U.S. Cl.** **257/31**; 257/33; 257/34; 257/36; 505/190; 505/193

(58) **Field of Classification Search** 257/34, 257/35, 36, 31; 505/190, 193; 438/2
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,605,822 B1 * 8/2003 Blais et al. 257/34
6,784,451 B2 * 8/2004 Amin et al. 257/34

OTHER PUBLICATIONS

Chiorescu, et al., "Coherent Quantum Dyamics of a Superconducting Flux Qubit", Mar. 21, 2003, Science, vol. 299, pp. 1869-1871.
Vion, et al., "Manipulating the Quantum State of an Electrical Circuit", May 3, 2002, Science, vol. 296, pp. 886-889.

* cited by examiner

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(57) **ABSTRACT**

A qubit (quantum bit) circuit includes a superconducting main loop that is electrically-completed by a serially-interconnected superconducting subloop. The subloop includes two Josephson junctions. A first coil provides a first flux that couples with the main loop but not with the subloop. A second coil provides a second flux that couples with the subloop but not with the main loop.

24 Claims, 2 Drawing Sheets